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CRUSTAL EMISSION AND THE QUIESCENT SPECTRUM OF THE NEUTRON STAR IN KS 1731–260

ROBERT E. RUTLEDGE[1], LARS BILDSTEN[2], EDWARD F. BROWN[3], GEORGE G. PAVLOV[4],
VYACHESLAV E. ZAVLIN[5] AND GREG USHOMIRSKY[1]

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ABSTRACT

The type-I X-ray bursting low mass X-ray binary KS 1731−260 was recently detected for the first time in quiescence by Wijnands et al., following a $\tau_{\rm outburst}\approx$13 yr outburst which ended in Feb 2001. We show that the emission area radius for a H atmosphere spectrum (possibly with a hard power-law component that dominates the emission above 3.5 keV) is consistent with that observed from other quiescent neutron star transients, R_∞=23^{+30}_{-15}(d/8 kpc) km, and examine possible IR counterparts for KS 1731−260. Unlike all other known transient neutron stars (NS), the duration of this recent (and the only observed) outburst is as long as the thermal diffusion time of the crust. The large amount of heat deposited by reactions in the crust will have heated the crust to temperatures much higher than the equilibrium core temperature. As a result, the thermal luminosity currently observed from the neutron star is dominated not by the core, but by the crust. This scenario implies that the mean outburst recurrence timescale found by Wijnands et al. ($\sim$ 200 yr) is a lower limit. Moreover, because the thermal emission is dominated by the hot crust, the level and the time evolution of quiescent luminosity is determined mostly by the amount of heat deposited in the crust during the most recent outburst (for which reasonable constraints on the mass accretion rate exist), and is only weakly sensitive to the core temperature. Using estimates of the outburst mass accretion rate, our calculations of the quiescent flux immediately following the end of the outburst agree with the observed quiescent flux to within a factor of a few. In this paper, we present simulations of the evolution of the quiescent lightcurve for different scenarios of the crust microphysics, and demonstrate that monitoring observations (with currently flying instruments) spanning from 1–30 yr can measure the crust cooling timescale and the total amount of heat stored in the crust. These quantities have not been directly measured for any neutron star. This makes KS 1731−260 a unique laboratory for studying the thermal properties of the crust by monitoring the luminosity over the next few years to decades.

Subject headings: stars: atmospheres — stars: individual (KS 1731−260) — stars: neutron — x-rays: binaries

1. INTRODUCTION

Brown, Bildsten & Rutledge (1998, BBR98 hereafter) argued that the core of a transiently accreting neutron star (NS) (for reviews of transient neutron stars, see Chen et al. 1997; Campana et al. 1998) is heated by nuclear reactions deep in the crust during the accretion outbursts. The core is heated to a steady state in $\sim10^4$ yr (see Colpi et al. 2000 for a detailed calculation), after which the NS emits a quiescent thermal luminosity (BBR98)

$$L_q = 8.7\times10^{33}\left(\frac{\langle\dot{M}\rangle}{10^{-10}M_\odot{\rm yr}^{-1}}\right)\frac{Q}{1.45{\rm MeV}}\ {\rm erg\ s^{-1}}, \quad (1)$$

where $\langle\dot{M}\rangle$ is the time-averaged (over the NS core thermal timescale) mass-accretion rate onto the NS, and Q is the amount of heat deposited in the crust per accreted nucleon (Haensel & Zdunik 1990; see Bildsten & Rutledge 2000 for a review). For an accretion flux onto the NS ($F_{\rm accretion}=\epsilon\dot{M}c^2/(4\pi D^2)$), the "rock bottom" quiescent flux due to deep crustal heating is then

$$F_q \approx \frac{\langle F_{\rm accretion}\rangle}{135}\,\frac{Q}{1.45{\rm MeV}}\,\frac{0.2}{\epsilon}, \quad (2)$$

where $\langle F_{\rm raccretion}\rangle \equiv \epsilon\langle\dot{M}\rangle c^2/(4\pi D^2)$ is the accretion flux averaged over the NS core thermal timescale, and the accretion efficiency $\epsilon=0.2$ for accretion luminosity of $(GM/R)\langle\dot{M}\rangle$.

Since $\langle\dot{M}\rangle=\dot{M}_{\rm outburst}(\tau_{\rm outburst}/\tau_{\rm rec})$, where $\tau_{\rm outburst}$ is the mean outburst duration and $\tau_{\rm rec}$ is the mean recurrence timescale, this scenario relates the quiescent luminosity to the outburst properties; comparisons to observations of several quiescent neutron stars (qNSs) match the predictions reasonably well (Brown et al. 1998; Rutledge et al. 2000). It also helps us to understand why the black hole systems in quiescence are so much fainter than NS systems (Garcia et al. 2001), as they cannot be thermally emitting. Equation (2) is the minimum quiescent flux from the neutron star. Should residual accretion occur in quiescence (Menou et al. 1999; Narayan et al. 1997), the accretion luminosity would be in addition to the thermal emission already present.

KS 1731−260 is a transient, type-I X-ray bursting neutron star approximately 3.8 degrees from the Galactic center (Van Paradijs 1995). It was discovered in outburst in 1989, when its luminosity was 1.3×10^{37} (d/8 kpc)^2 erg s^{-1}; subsequent analysis found that it had been in outburst at least since Oct 1988 (Sunyaev 1989; Sunyaev et al. 1990), and has remained bright since then (see Wijnands et al. 2001a for a complete description of observations). Sunyaev et al. (1990) suggested that it was a transient, apparently because it had not previously been detected, although no strong upper limits on previous X-ray emis-

[1] Theoretical Astrophysics, California Institute of Technology, MS 130-33, Pasadena, CA 91125; rutledge@srl.caltech.edu, gregus@tapir.caltech.edu
[2] Institute for Theoretical Physics and Department of Physics, Kohn Hall, University of California, Santa Barbara, CA 93106; bildsten@itp.ucsb.edu
[3] Enrico Fermi Institute, University of Chicago, 5640 South Ellis Ave, Chicago, IL 60637; brown@flash.uchicago.edu
[4] The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802; pavlov@astro.psu.edu
[5] Max-Planck-Institut für Extraterrestrische Physik, D-85740 Garching, Germany; zavlin@xray.mpe.mpg.de

sion were given. (This was noted later by Barret et al. (1998), who suggested the object may not be a transient at all. We adopt an outburst timescale of $\tau_{\rm outburst} \approx 13$ yr, although the outburst may have been longer). Type I X-ray bursts were observed, at the rate of $\sim$10 per day, and studied in detail with RXTE (Muno et al. 2000). Nearly coherent oscillations (580 Hz) have been observed during the type-I bursts, and the frequency is interpreted as the spin frequency of the NS (Smith et al. 1997). The uncertainty in the localization of this source was initially $4.2'$ (90% confidence). An improved error circle ($10''$ with *ROSAT*/HRI; Barret et al. 1998) found 13 candidate IR counterparts down to $J = 15.4$ (10 σ). The integrated HI column density in the direction of KS 1731–260 is $N_{\rm H,22}$=0.35 [6] (N_H =$N_{\rm H,22} 10^{22}$ cm^{-2}). Barret et al. (1998) found $N_{\rm H,22}$=1–6 (A_V=5–34; Predehl & Schmitt 1995), suggesting that $N_{\rm H}$ is variable, and thus there must be significant contribution to $N_{\rm H}$ from the system itself.

An *RXTE*/PCA scan of the Galactic Center found that KS 1731–260 had entered a low luminosity state (Wijnands et al. 2001a) in early 2001. Wijnands et al. (2001a) then observed the source with *Chandra*/ACIS-S in late March ($\sim$1 months after the end of the outburst) and detected it at an unabsorbed flux of $\sim 2\times10^{-13}\,{\rm erg\,cm^{-2}\,s^{-1}}$ (0.5–10 keV).

1.1. *Crust Thermal Emission*

The scenario described by equation (2) applies when the neutron star crust and atmosphere resemble that of a cooling neutron star – that is, the temperature decreases with increasing radius. For NS transients with short outbursts, such as Aql X-1 ($\tau_{\rm outburst} \sim 30\,$d), this is a good approximation, as the increase in crust's temperature from the heating during the outburst is small (Ushomirsky & Rutledge 2001). This is not the case for KS 1731–260. The duration of its most recent outburst is of the order of (or longer than) the thermal diffusion timescale in the crust (BBR98). In a sense, KS 1731–260 in quiescence resembles a neutron star that accreted steadily at the *outburst* accretion rate, except that the core temperature will be at the lower value set by the time-averaged accretion rate (over the previous $10^4\,$yr).

To illustrate how the crust is so dramatically heated during a long outburst, consider the rise in temperature if no heat were conducted away from the crust during the outburst. As we describe in § 3.3, the total heat capacity of the region of the crust where most of the heat is deposited is $C \sim 5\times10^{35}$ erg K^{-1}. During the outburst, the total amount of heat deposited is $Q\dot{M}_{\rm outburst}/m_p \approx 10^{44}\,$erg and so, *if no heat is conducted away from the heating region*, the temperature there can rise to 2×10^{8} K during the 13 year outburst. Even when thermal conduction is taken into account, the rise in crust temperature can still be $> 5\times10^{7}\,$K, which is the typical temperature the crust and core would have if KS 1731–260 accreted steadily at $\langle\dot{M}\rangle = \dot{M}_{\rm outburst}(\tau_{\rm outburst}/\tau_{\rm rec}) \approx 2.6\times10^{-11} M_\odot$ yr^{-1} (for $\tau_{\rm rec} \approx 1500$ yr; see § 3.2).

If the crust, which is composed of the ashes of H/He burning, has a low thermal conductivity, then there is a substantial temperature gradient between crust and core. As discussed by Brown (2000) for the case of steadily accreting neutron stars, when there is a substantial thermal gradient in the inner crust, the temperature of the crust reaction layers becomes decoupled from that of the core.

For the NS in KS 1731–260, this means that, until the crust has thermally relaxed, we cannot directly infer its core temperature, as is possible for short-outburst transients such as Aql X–1. However, this also means that one can directly compute the current quiescent luminosity from KS 1731–260 using the fluence during the last outburst, as the thermal state of the crust is only weakly sensitive to the temperature of the core, and, hence, is nearly independent of the uncertainty in the accretion history over the past $\sim 10^4$ yrs (the thermal time of the core), unlike in the case of short-outburst transients. Our simulations, presented here, predict a quiescent luminosity which agrees with the observed value to within observational and theoretical uncertainties (factor of a few) for the fiducial value of Q and outburst fluence. Moreover, this dependence of the thermal flux in the crust-dominated regime on $\dot{M}_{\rm outburst}$, and not on $\langle\dot{M}\rangle$, allows us to predict the evolution of L_q, which can be directly confronted with observations.

The domination of the quiescent luminosity by the cooling crust sets KS 1731–260 apart from the other neutron star transients with short duration outbursts and makes it an ideal laboratory for separately measuring the thermal properties of the crust.

1.2. *Outline of the Paper*

In this paper we report our analysis of the *Chandra* observation (Wijnands et al. 2001a) of KS 1731–260 in quiescence and describe our simulations of the thermal state of its crust and core. We begin in § 2 by describing the *Chandra* observation and spectral analysis of KS 1731–260. We include a description of possible IR counterparts (§ 2.2). After describing the observations, we then discuss the implications for the crust and core thermal structure as outlined above. We first apply (§ 3.2) the scenario in which the crust heating for any single outburst is negligible, i.e., we treat KS 1731–260 as if it were a short-duration outburst, such as Aql X-1. This analysis has been done previously by Wijnands et al. (2001a). We then explain, in § 3.3, why this analysis is inapplicable to this source, and how the quiescent luminosity is determined by the thermal properties of the crust (its thermal diffusion timescale and heat capacity) for the next 1–30 yr. We present simulations of the quiescent lightcurve and demonstrate that monitoring observations can constrain these properties, similar to proposals for glitching pulsars (Van Riper et al. 1991; Chong & Cheng 1994; Hirano et al. 1997; Cheng et al. 1998). We conclude in § 4 with a summary and discussion of these results.

2. *Chandra* OBSERVATIONS

The data were obtained from the *Chandra* public archive. The discovery and observations have been previously analyzed by Wijnands et al. (2001a), and details of the trigger and history of KS 1731–260 are included there. The observation was triggered when an *RXTE*/PCA scan of the Galactic Center found that KS 1731–260 had entered a low luminosity state (Wijnands et al. 2001a), and was made 2001 Mar 27 00:18-06:23 (TT) with the ACIS-S instrument (Weisskopf 1988) for a total exposure time of 19401 seconds. The X-ray source was imaged on the S3 (backside illuminated) chip, which was operated as a 1/4 array with 0.8 sec exposures. We analyzed the data using the CIAO v2.1 [7] with CALDB v2.6 and XSPEC v11 (Arnaud 1996).

[6] W3nH, at http://heasarc.gsfc.nasa.gov; Dickey & Lockman 1990

[7] http://asc.harvard.edu/ciao2.1/

Two X-ray point sources separated by 31.3±0.1″ are found with *celldetect* above a signal/noise ratio of 5, listed in Table 1. We compared this image with an archived *ROSAT*/HRI image of this region (rh400718)[8] taken in 1997 when KS 1731–260 was in outburst. The position of KS 1731–260 had been previously determined this way (Barret et al. 1998) and clearly KS 1731–260 is at the position of *Chandra* source #1.

X-ray source counts were extracted within an area 5 pixels in radius about the KS 1731–260 source position, for a total of 183 counts. At 0.0075 counts/frame, the pileup fraction is negligible. Background was taken from an annulus centered on the source position, with radii of 10 and 80 pixels. The expected number of background counts in the source region is 3. A KS test (Press et al. 1995) finds that the times of arrival (TOA) of the 183 counts is consistent with a constant countrate. We place 3σ upper-limits on variability of $3\times 1./\sqrt{183\ \text{counts}}$=22% rms. We also produced a power-density spectrum to search for a pulsed signal (number of frequency bins: 12750, with frequency resolution of 5×10^{-5} Hz, and a Nyquist frequency of 0.625 Hz; see Press et al. 1995), using barycentered TOAs (tool *axbary*). No evidence for a pulsed signal is found: the largest Leahy-normalized power (Leahy et al. 1983) was 20.37 (with a probability of chance occurrence from a Poisson-distributed countrate of 0.48). The absence of a coherent signal is not surprising in light of the detection of pulsations during type-I X-ray bursts (Muno et al. 2000) at ∼580 Hz, well above our Nyquist frequency.

2.1. *Spectral Analysis of KS 1731–260*

We binned the KS 1731–260 data into 10 PI bins (0.5-10.0 keV), and fit several single component spectral models (power-law, H atmosphere, or Raymond-Smith, a multicolor disk and blackbody). Galactic absorption is initially left as a free parameter. The best-fit models were all statistically acceptable; the parameters are given in Table 2.

While all models we investigated are statistically acceptable, some can be argued against on physical grounds. The pure power-law spectrum is unusually steep (α=5.2±0.6), typical more of a thermal spectrum than other processes. The emission measure $\int n_e n_h dV$ from the Raymond-Smith spectrum is higher by 2 orders of magnitude than typical from active stellar coronae in the analogous RS CVn systems (Dempsey et al. 1993a; Dempsey et al. 1993b; see Bildsten & Rutledge 2000 for discussion on coronal emission from companions in X-ray transients). The disk black-body spectral model implies an inner disk radius of ∼0.7 km – considerably smaller than a neutron star. Our best-fit blackbody spectrum is consistent with that found by Wijnands et al. (2001a).

As pointed out by BBR98, for accretion rates $\lesssim 2\times10^{-13}$ $M_\odot\,\text{yr}^{-1}$, gravity stratifies metals in the NS atmosphere faster than they can be provided by accretion (Bildsten, Salpeter, & Wasserman 1992), making a pure H atmosphere the appropriate description of the NS photosphere in quiescence. Due to the strongly energy-dependent opacity of free-free transitions, these spectra are significantly different from blackbodies (Rajagopal & Romani 1996; Zavlin et al. 1996). Unlike the results from black-body fits, the inferred NS radii ($R_\infty = r/\sqrt{1-2GM/(rc^2)}$ where r is the proper radius, and ∞ means the value as measured by a distant observer) of the four observed field transients using H atmosphere spectra are consistent with what are expected theoretically: $R_\infty\sim$12 km (Cen X–4, Rutledge et al. 2001c; Aql X–1, Rutledge et al. 2001a; 1608-522 Rutledge et al. 1999; and 4U 2129+47 Rutledge et al. 2000), thus supporting the notion that much of the emission originates from a neutron star surface.

The quiescent spectrum for qNSs is thus interpreted as thermal emission from a pure Hydrogen atmosphere NS, possibly with an underlying power-law (whose origin is not understood) which dominates the spectrum at high (>3 keV) energies (see Rutledge et al. 2001c; 2001a). The spectral fit for a H atmosphere spectrum alone (no power-law) gives $kT_{\rm eff}^\infty$=120±30 eV, an emission area radius of $R_\infty=10^{+10}_{-5}$ (d/8 kpc) km, and an unabsorbed flux of 1.8×10^{-13} erg cm^{-2} s^{-1}(0.5-10 keV; the absorbed flux is 3.8×10^{-14} erg cm^{-2} s^{-1}), corresponding to a luminosity of $L_X = 1.4\times10^{33}$ (d/ 8 kpc)^2 erg s^{-1}(0.5-10 keV). The 90% confidence range in the unabsorbed flux is (1.1–4.6)$\times10^{-13}$ erg cm^{-2} s^{-1}. The best-fit spectrum is shown in Fig. 1. The bolometric thermal luminosity (as observed at infinity) is $L_{\rm bol,\infty} = 4\pi R_\infty{}^2\sigma(T_{\rm eff}^\infty)^4$ =2.7×10^{33} (d/8 kpc)^2 erg s^{-1}(uncertain by a factor of ∼3, due largely to spectral uncertainty). If 100% of the emergent luminosity were from accretion (at an efficiency of 0.2), this sets $\dot{M} = 2.3\times10^{-13}$ $M_\odot\,\text{yr}^{-1}$, sufficiently low for the assumption of an H atmosphere.

When we include an underlying power-law with all parameters free, the S/N of the spectrum does not constrain the model parameters to better than an order of magnitude. When we hold R_∞ and α fixed at typical values (R_∞=12.5 km for d=8 kpc; $\alpha = 0.85$; cf. Rutledge et al. 2001c; Rutledge et al. 2001a), the spectral model provides an acceptable fit to the data. This demonstrates that the spectrum of KS 1731–260 in quiescence is consistent with that observed from other qNSs.

2.2. *Possible Infrared Counterparts*

A comparison between Chandra astrometry and 2MASS images finds a possible IR counterpart at the position of source #2 (see below) but not of KS 1731–260, with limits in J, H and K_s of 15.8, 15.1 and 14.3 magnitudes respectively [9]. Comparing with IR sources previously examined as possible counterparts to KS 1731–260 (Barret et al. 1998), the closest object is source "H", which is 1.5±1.1″ away (we adopt 1″ positional uncertainty for *Chandra*, and 0.5″ uncertainty for the IR source). The second closest is "G", which is 3.3″ away. In addition, there is a fainter IR object present in the H-band image ("new" object), but not in the J-band image taken by Barret, which is not marked, but which is consistent with the *Chandra* position for KS 1731–260. Further work in the IR – for example, searching for ellipsoidal variations in quiescence – is needed for a positive identification of the counterpart.

Source #2 is consistent in position with 2MASS J173412.7-260548 (r = 0.46″ in distance, about the accuracy of the 2MASS position reconstruction error). For an IR field source density of $\rho=6.9\times10^{-3}$ arcsec^{-2} (217700 objects in the 2MASS catalog within a 1000″ radius) the probability of a chance coincidence is prob=$1-\exp(-4\pi r^2\rho)$=3.9%, which is the significance of the association of the X-ray and IR objects. The source's 2MASS magnitudes and colors are J=12.264±0.033, $J-H$=0.948 and $J-K_s$=1.33.

When this work was largely complete, Wijnands et al. (2001b) used relative astrometry with 2MASS, and found

[8]http://heasarc.gsfc.nasa.gov

[9]http://www.ipac.caltech.edu/2mass/overview/about2mass.html

that the *Chandra* localization is coincident with the "new" object and not "H" and "G".

3. CORE DOMINATED EMISSION, CRUST DOMINATED EMISSION, AND THE FUTURE LIGHTCURVE OF KS 1731–260

Having described the observations and spectral analysis of KS 1731–260, we now turn our attention to the thermal properties of the neutron star's crust and core. We begin by estimating the amount of mass deposited during the previous outburst; we then describe what the thermal structure would be if the change in crust temperature during this outburst were small (BBR98; Wijnands et al. 2001a). This is the case for transients with short-duration outbursts. Because of the length of the outburst for this source, however, the crust is substantially heated; § 3.3 describes how the observed emission is determined by the heating of the crust during the past outburst, and not by the core equilibrium temperature. Using the method of UR01, we simulate the evolution of the quiescent lightcurve for different regimes of the crust and core microphysics.

3.1. *The Outburst Fluence*

KS 1731–260 has been observed several times, always in outburst, since 1988, and nearly continuously so since Jan 1996 with the *RXTE*/ASM[10]. To estimate $\langle F_{\rm outburst}\rangle$, we integrated the ASM counts using only data in which there was a $> 3\sigma$ 1-day detection and taking only 1 day detections in which the previous observation was made $<$4 days (to insure adequate sampling) prior. Periods in which the time to the previous observation was $>$4 days were not included. The total fluence is 13660 ASM c/s$\times$days, over an integration of 1599 days (including both detections and non-detections). If we assume an additional countrate at the 2σ level on those observations when the countrate was below 3σ detection, the total fluence would only increase by 7%, which is our 2σ upper-limit for the uncertainty in integrated counts. Assuming a $kT_{\rm bremss}$=5 keV bremsstrahlung spectrum with $N_{\rm H,22}$=1.0 (which gives $6.5\times10^{-10}\ {\rm erg\,cm^{-2}\,s^{-1}}$per 1 ASM c/s, corrected for absorption, 0.01–20 keV, from W3PIMMS [11]; in the 2–10 keV range, the conversion factor is $3.0\times10^{-10}\ {\rm erg\,cm^{-2}\,s^{-1}}$per 1 ASM c/s), we find a mean outburst flux, corrected for absorption, of $13660\,{\rm ASM\ c/s}\times\ {\rm d}/1599\ {\rm d}\times\ (6.5\times10^{-10}\ {\rm erg\,cm^{-2}\,s^{-1}}$ per 1 ASM count) = $5.6\times10^{-9}\ {\rm erg\,cm^{-2}\,s^{-1}}$. We conservatively estimate the spectral uncertainty to be at the 40% level (for a change in $kT_{\rm bremss}$ between 2 keV and 8 keV, the ASM counts/flux conversion changes by 40%). Extrapolating this mean to the entire outburst, we find an outburst fluence of $\mathcal{F}$ = $5.6\times10^{-9}\,{\rm erg\,cm^{-2}\,s^{-1}}\times(13\,{\rm yr}\times3.2\times10^{7}\,{\rm s/yr}) = 2.3\,{\rm erg\,cm^{-2}}$. This estimate is greater by a factor of $\sim$6 than that of Wijnands et al. (2001a), who estimated $\mathcal{F}$ using the minimum observed outburst flux and an outburst duration of 11.5 yr, rather than 13 yr.

3.2. *A First Estimate: Core-Dominated Emission*

The quiescent bolometric thermal flux is $F_q = 3.5\times10^{-13}\,{\rm erg\,cm^{-2}\,s^{-1}}$. If the change in crust temperature during the outburst were small, then equation (2) would apply: the time-averaged accretion flux is $\langle F_{\rm accretion}\rangle = \mathcal{F}/\tau_{\rm rec}$, so that

$$\tau_{\rm rec}\approx\frac{\mathcal{F}}{135F_q}\,\frac{Q}{1.45\ {\rm MeV}}\,\frac{0.2}{\epsilon}=1500\,{\rm yr}. \qquad (3)$$

There is an uncertainty of about ±0.5 dex in this value, mostly due to the uncertainty in the bolometric value of F_q. This estimate is similar to the one arrived at independently by Wijnands et al. (2001a), although our estimated mean recurrence time is longer (1500 $\pm$0.5 dex yr vs. 200 yr), since our time-averaged outburst flux is a factor of six greater than that assumed by Wijnands et al. (2001a).

Strictly speaking, this estimate of $\tau_{\rm rec}$ is the recurrence time to an outburst of comparable fluence. A month-long outburst would have just 1% of the fluence of the previous outburst and would not affect the estimate of eq. (3). This estimate also neglects any neutrino emission, which reduces the effective value of Q and hence $\tau_{\rm rec}$. More seriously, however, this analysis ignores the fact that the crust is strongly perturbed away from the core equilibrium temperature during such a long outburst. As a result, the quiescent emission currently observed is set by the thermal relaxation of the heated crust, and as we now demonstrate, is mostly decoupled from the thermal state of the core.

3.3. *Crust Dominated Emission*

During an outburst, the heating from the reactions raises the temperature in the crust around the reaction layers. After the outburst ends, the crust thermally relaxes and the thermal profile comes to resemble a cooling neutron star, i.e., the temperature decreases with radius. For neutron star transients with "typical" outburst fluences and recurrence times (that is, $\tau_{\rm outburst}\sim1$ month, with an outburst luminosity ~0.1 Eddington), the variations in the crust temperature and hence L_q are small (BBR98; UR01). For example, UR01 found that L_q varied by $\sim$ few% for $\tau_{\rm rec}$ = 1 yr and by $\sim$ 30% for $\tau_{\rm rec}$ = 30 yr. The variation is small because the amount of energy deposited in such short outbursts is not significant compared to the heat content of the crust, and so the crust is not heated substantially compared to its temperature when in thermal equilibrium with the core.

As our order of magnitude estimate of the crustal temperature for KS 1731–260 in § 1.1 demonstrates, the situation is completely different in the case of KS 1731–260, with its $\tau_{\rm outburst}\approx13$ yr outburst.

To ascertain the magnitude of the deviation of L_q from the value predicted by Eq. (1), we performed several simulations of thermal relaxation of the NS crust in a transient with observational properties ($\tau_{\rm outburst}$, $\tau_{\rm rec}$, $F_{\rm outburst}$) inferred for KS 1731–260 using the methods and microphysics as described in UR01. In summary, we solve the non-relativistic heat equation in the crust, from $\rho\approx10^{8}$ g cm^{-3} to 1.5×10^{14} g cm^{-3}. Heating due to nuclear reactions in the deep crust is simulated by depositing energy at densities corresponding to the nuclear transitions computed by Haensel & Zdunik (1990), with the amount of energy set by the instantaneous accretion rate. At the outer boundary, we use the flux-temperature relation for a fully accreted crust from Potekhin et al. (1997). The core is taken to be isothermal (a good assumption for the timescales of interest because of the large thermal conductivity), and its temperature evolves according to the mismatch between its neutrino emissivity and the flux from the crust. We start our simulations with the temperature profile corresponding to persistent accretion at the rate $\langle\dot{M}\rangle$ corresponding to the time average of $\dot{M}_{\rm outburst}$ over

[10]http://xte.mit.edu

[11]http://heasarc.gsfc.nasa.gov

the recurrence time. We then evolve the model through several outburst/quiescence cycles, as necessary for the model to "forget" the initial conditions and reach a limit cycle.

If the crust resembles that of a neutron star steadily accreting at $\dot{M}_{\rm outburst}$, then the estimate of the recurrence time (eq. [3]) is inapplicable (except as a lower limit). This is because the crust temperature is decoupled from that of the core. A full survey of parameter space should include simulations over a range of $\tau_{\rm rec}$. This is beyond the scope of this initial paper; rather, we presume that $\tau_{\rm rec}$ is given by eq. (3) in order to survey the influence of the crust and core microphysics.

In these simulations, we examine the two main uncertainties in NS microphysics, (1) the impurity fraction, and, hence, the conductivity of the crust and (2) the possible presence of "enhanced" core neutrino cooling mechanisms,[12] such as direct Urca or pion condensation. First, the composition of accreting NS crusts is set by the nuclear processing of products of burning in the upper atmosphere. Published calculations (Sato 1979; Haensel & Zdunik 1990) presume that burning proceeds to pure iron, and, hence, the crust has no impurities. However, recent work by Schatz and collaborators (Schatz et al. 1999; Schatz et al. 2001) shows that burning products are a mix of elements substantially heavier than iron, with the impurity parameter[13] $Q_{\rm imp}$ comparable to the square of the average nuclear charge $\langle Z\rangle^2$. We therefore set bounds on the crustal conductivity by using electron-ion scattering (Yakovlev & Urpin 1980), which has the same form as electron-impurity scattering with $Q_{\rm imp} = Z^2$, and electron-phonon scattering (Baiko & Yakovlev 1995), which is appropriate for a pure crystal. We refer to these two cases as "low K" and "high K", respectively. Second, the uncertainty in core cooling is covered by simulations with "standard cooling" and "enhanced cooling" (modified Urca appropriately suppressed by nucleon superfluidity, and neutrino emission as when the core is a pion condensate, respectively; see UR01 for details).

To illustrate the deviation of the crustal temperature from the equilibrium core temperature and the subsequent thermal relaxation of the crust, we show in Fig. 2 the time evolution of the crustal temperature in the low K, standard cooling case for observational parameters inferred for KS 1731–260 ($\tau_{\rm rec}$ = 1500 yr, $\tau_{\rm outburst}$ = 13 yr, and $\dot{M}_{\rm outburst} = 3\times10^{-9}M_\odot$ yr^{-1}). Vertical slices of the surface in the density-temperature plane show the instantaneous temperature distribution in the crust, while slices in the time-temperature plane show the time evolution of the temperature since the beginning of the outburst. Clearly, the crust is heated to well above its pre-outburst temperature profile, which tracks the core temperature (note that, because the crust is heated to well above its temperature in equilibrium with the core, this qualitative result is not very sensitive to the assumed $\tau_{\rm rec}$). A steep temperature gradient carries most of the heat from the deep crustal heating region around 10^{12}–10^{13} g cm^{-3} into the core, while a shallower temperature gradient carries a fraction of the heat towards the surface. The temperature near the top of the crust ($\sim 10^{10}$ g cm^{-3}; and, hence, the X-ray luminosity, $L_q \propto T_{\rm top}^{2.4}$; Potekhin et al. 1997) reaches a maximum at the end of the outburst (time=13 years), and then decays back to the pre-outburst value on the thermal timescale of the crust ($\sim$ 30 yrs for this model). Thermal evolution in other cases is similar (but, of course, is different in the absolute magnitude of the temperature change), and the temperature changes are always much bigger than those that occur during short-duration outbursts (cf. Fig. 1 of UR01).

In Fig. 3, we show the long-term evolution of the quiescent surface luminosity from KS 1731–260 after accretion onto the compact object has ceased for the four cases discussed above, namely, low and high crustal conductivity K, and standard and enhanced core neutrino emission (see the legend on the plot). First consider Fig. 3a, where we set $Q = 1.45\,$MeV. In all four cases, the transition from crust-dominated (at early times) to core-dominated cooling (at late times) is evident as a drop in the luminosity, ranging from 50% (high K, standard cooling case) to a factor of 100 (low K, enhanced cooling case). Regardless of the core neutrino emissivity, this transition occurs at ~ 30 yrs for low conductivity crusts, and after ~ 1 yr for high conductivity crusts. These timescales are easy to understand, as they are just the thermal time to the appropriate depth in the crust (cf. Figure 3 of UR01). Since the low K crust has a longer thermal time, it stays hot about 30 times longer than the high K crust.

After the crust thermally relaxes, L_q is set by the emission from a hot core. If the only core neutrino emission mechanism is modified Urca, suppressed by nucleon superfluidity, then the amount of heat lost by neutrinos from the core is negligible. Therefore, all the heat deposited into the star comes out as thermal emission, and L_q asymptotically approaches the value given Eq. (1), with $Q \approx 1.45$MeV (see solid and dashed lines in Fig. 3). On the other hand, when enhanced neutrino cooling is allowed, $\sim 90\%$ of the deposited heat escapes as neutrinos (Colpi et al. 2000; UR01), and only the remaining $\sim 10\%$ is radiated thermally from the surface. In this case, the "effective" value of Q in Eq. (1), in the sense of the energy retained in the star and re-radiated thermally, is $Q \approx 0.1$MeV.

As shown above, the crust is heated to well above the core temperature during the long outburst. How does the temperature difference between the crust and the core depend on the crustal conductivity? As an estimate, we can assume that, during the outburst, the crust comes to an equilibrium where the heat deposited around $\rho \approx 10^{12}-10^{13}$ g cm^{-3} at a rate $\dot{E}$ is conducted away from this region. This is a very good assumption for the high conductivity case, and an acceptable one for the low conductivity case, where the crustal thermal time is comparable to the outburst duration. During the outburst, most of the heat is conducted into the core with a flux $F \approx K(T_{\rm crust}-T_{\rm core})/\Delta r$, where $\Delta r \approx 500$ m is the distance between the crustal heating region and the core. Thermal balance then requires $\dot{E}/4\pi R^2 \approx K(T_{\rm crust}-T_{\rm core})/\Delta r$, or $T_{\rm crust}-T_{\rm core} \approx 1.2\times10^8$ K $/K_{19}$, where K_{19} is the conductivity in units of 10^{19} erg cm^{-1} s^{-1}K^{-1}. In the low conductivity case, $K_{19}\sim 1$, so $T_{\rm crust} \gg T_{\rm core}$. We see from Fig. 3a that L_q at early times in the low K case is the same for standard and enhanced cooling (solid and dotted lines). This is now easy to understand, since, as we showed above, the crustal temperature is decoupled from the core temperature if the conductivity is low. This situation is exactly the same as for persistent accreters discussed by Brown (2000). On the other hand, for high conductivity crusts, $K_{19} \gtrsim 10$, so $T_{\rm crust}$ can not significantly deviate from $T_{\rm core}$ during the outburst. Therefore, crust-dominated L_q in the high K case (dashed and dash-dotted lines in Fig. 3a) more closely reflects the core temperature, which is quite different between the standard and enhanced cooling

[12] Neutrino emission due to crustal bremsstrahlung is insignificant at the relevant temperatures, but is included in all models.

[13] The impurity parameter is the deviation of the nuclear charges Z of the elements of the mix from the average charge $\langle Z\rangle$, $Q_{\rm imp} = \langle (Z-\langle Z\rangle)^2\rangle$, where the average takes into account the relative abundance of the species.

cases.

From examination of lightcurves in Figs. 3a, it is likely that KS 1731–260 was observed in quiescence during the crust-dominated phase, and is presently evolving through this phase. In three of four cases considered in Fig. 3a, the predicted quiescent luminosity L_q right after the outburst is a factor of 3 higher than the observed $L_{\rm bol}$ (itself uncertain by a factor of 3, due to spectral uncertainty). Since L_q depends directly on $Q\int \dot{M}_{\rm outburst}dt$ over the outburst duration, this difference could also be due to a systematic overestimate of $\dot{M}_{\rm outburst}$ during the ≈ 13 yr outburst, only the last 5 years of which have been covered $\sim$ daily with RXTE/ASM. Alternatively, this difference could be due to a value of Q different from the fiducial, since the exact value of Q is uncertain (see Schatz et al. 1999, 2001 for a discussion on different crustal compositions than assumed by Haensel & Zdunik 1990). To provide lightcurves which extrapolate from the currently observed luminosity, in Fig. 3b we adjusted Q (or, equivalently, $\int \dot{M}_{\rm outburst}dt$) by factors of 0.3 to 2, as noted in the figure caption, to obtain $L_q \sim 2.7\times10^{33}$ erg s^{-1} at the start of quiescence.

We stress that the overall normalization of these lightcurves is uncertain due to uncertainty in Q and outburst fluence, but the shape is determined by the microphysics of the crust and the temperature of the core. The time evolution of the luminosity will permit distinction between the four cases, and, hence, directly infer the integrated conductivity of the crust and possibly indicate whether enhanced neutrino emission mechanisms are operating in the core. In particular, observing the drop in the luminosity will permit the measurement of the thermal timescale of the crust. In addition, the relative magnitude of the drop will tell us about the presence or absence of enhanced neutrino emission from the core. Such measurements (accurate to $\lesssim$10%) are well within the capabilities of present X-ray instrumentation, as the present detection demonstrates. Observations over the next year will be able to exclude the case where the crust is a pure crystal and hence has very high conductivity.

Since the initial understanding of Type I bursts as thermonuclear flashes, there has been an open question as to how much flux is rising up from deep parts of the star into the burning region (see Paczynski 1983; Bildsten 1995). Large values of this flux ($\sim$ 1 MeV per accreted nucleon) can stabilize burning at accretion rates lower than otherwise expected. Brown (2000) first showed that most of the crustal heating in a persistent source went into the NS core and that, at most, 100 keV per accreted nucleon came out into the upper parts of the star. The quiescent observations of KS 1731–260 shortly after outburst strongly support this picture and tell us that deep nuclear heating will not impact the Type I X-ray burst behavior.

Assuming that the source has been transiently accreting for the past 10^4 yr or so, with outburst fluences similar to that of the most recent observed outburst, we can constrain the core temperature to be less than the maximum crust temperature. To determine the most conservative (i.e., largest) upper bound on this peak crust temperature, we use the following assumptions. We take the atmosphere to be composed of pure iron (which has a higher opacity than hydrogen/helium) and we use low thermal conductivity (electron-ion scattering) in the crust. These assumptions lead to the largest temperature rise between the photosphere and the crust. Taking $kT_{\rm eff}$ = 130 eV, we find a peak crust temperature, and hence a maximum core temperature, of 3.5×10^8 K.

4. DISCUSSION AND CONCLUSIONS

The large amount of heat deposited during the recent (and the only observed) outburst of KS 1731–260, and the lengthy duration of the outburst compared to the thermal diffusion time of the NS crust, imply that the quiescent flux recently observed is dominated by emission from the cooling crust and not the core. The importance of this result is that the quiescent luminosity *is calculated using the properties of only the most recent outburst*, rather than by estimating the accretion history over the past 10^4 yr, as is the case in the core-dominated transients such as Aql X–1 and Cen X–4 (Rutledge et al. 2001c; Rutledge et al. 2001a). Our prediction of the quiescent luminosity from the cooling crust following the outburst agrees, to within observational and theoretical uncertainties (a factor of a few), with the estimate of the observed bolometric luminosity. Unlike the case of the short $\tau_{\rm outburst}$ transients where we can directly infer the average core temperature, in the case of KS 1731–260 we cannot measure the core temperature, and hence the recurrence time, until after the crust has thermally relaxed (1–30 yr after the end of the outburst). Assuming that the source has been transiently accreting for the past 10^4 yr or so, with outburst fluences comparable to that of the most recent outburst, we can constrain the core temperature to be less than the peak crust temperature, which, using the relation of Potekhin et al. (1997) for an iron crust (low conductivity), gives $T_{\rm core}\lesssim 2\times10^8$ K.

We predict future lightcurves for KS 1731–260 on the basis of 4 different scenario for crustal and core microphysics (high/low conductivity, and enhanced/normal neutrino emissivity). These can be distinguished from each other observationally – one in $<$1 yr (excluding or confirming the high K crust with enhanced neutrino emissivity core), others over longer terms (10-100 yrs). This offers the unique opportunity to directly constrain the properties of the NS crust – thermal conductivity, heat capacity, and depth to the NS core – through monitoring observations that would measure the predicted decaying lightcurve.

KS 1731–260 is now the fifth—after Cen X–4, Aql X–1, 4U 1608-522, and 4U 2129+47—field transient neutron star which displays in quiescence a spectrum consistent with a H atmosphere NS of radius $R_\infty\sim$ 12 km, and (possibly) a hard ($\alpha\sim$0.85) power-law component which comprises 10–40% of the quiescent (0.5–10 keV) flux. KS 1731–260 shows no variability on short ($<$hours) timescales. These spectral and variability properties are identical to those of the well-studied Aql X–1 and Cen X–4 (Rutledge et al. 2001c; Rutledge et al. 2001a), and the spectral properties are similar to those from lower S/N data of 4U 1608-522 and 4U 2129+47 (Rutledge et al. 1999; Rutledge et al. 2000). The derived radius is also comparable to that derived from this object using the independent method of a cooling radius expansion burst (Smith et al. 1997).

It is possible that a persistent source can turn off after long periods of accretion (here, a persistent source is one accreting for a period $\gg10^4$ yr, the core heating timescale). While Eq. 1 would seem to be applicable to predict the post turn-off quiescent thermal luminosity from the crust, the equation assumes that all heat deposited in the crust is re-radiated during quiescence. That will not be the case for sources approaching Eddington luminosity, such as KS 1731–260, where the effect of neutrino cooling in the crust and core cannot be neglected. In such cases, $L_q\approx Q_{\rm crust}(\dot{M}_{\rm outburst}/m_p) = 9\times10^{33}(Q_{\rm crust}/150\,{\rm eV})(\dot{M}_{\rm outburst}/10^{-9}\,M_\odot\,{\rm yr}^{-1})$. Here $Q_{\rm crust}$ is the

energy per accreted baryon emitted through the atmosphere from the crust immediately following the outburst. A minimum value, $Q_{\rm crust} = 0.1Q \approx 150$ eV/nucleon, applies when the source accretes persistently at the Eddington limit, in which only 10% of the deposited heat flows towards the surface (Brown 2000). At lower persistent luminosities, however, the crust and core temperatures are lower and neutrino cooling in each becomes less important, so $Q_{\rm crust}$ increases. In the case of KS 1731–260 ($L_{\rm outburst} \sim 0.1 L_{\rm Edd}$), we obtain $Q_{\rm crust} \approx$250 eV, if KS 1731–260 were a persistent accreter. However, the quiescent luminosity of KS 1731–260 gives instead $Q_{\rm crust}$ = 20 eV, a factor of 7 below the lower limit, even for a persistent source accreting at the Eddington rate. This demonstrates that KS 1731–260 cannot be a persistent accreter, because its crust (and by extension the core) is too cool to have been accreting for $\gg 10^4$ yr. Note, however, that we have neglected the effect of of neutrino emission due to Cooper pairing of superfluid particles (see Yakovlev et al. 2001 for a review) which may reduce the value of $Q_{\rm crust}$.

As discussed by Rutledge et al. (2000), the study of qNSs in globular clusters has yielded a new way to accurately measure NS radii. The distances to some globular clusters have been determined to $\lesssim$2% post-Hipparcos (Carretta et al. 2000), and can be measured even more directly with SIM (Unwin 1998), effectively removing distance as an uncertainty. At present, there is only one globular cluster qNS in which the thermal component has been spectroscopically analyzed (in ω Cen; Rutledge et al. 2001b) and there are two more proposed (in 47 Tuc; Grindlay et al. 2001). Measuring NS radii to an accuracy of $\pm$0.5 km—even without knowing the mass—can exclude $\sim$50% of the proposed equations of state for the NS core matter (Lattimer & Prakash 2001). Even though we presently cannot make such accurate radius measurements in the field transients due to uncertain distances (which can be overcome with SIM), they remain important targets for detailed studies of the observational phenomena of qNSs, such as we report here.

The relative luminosity of the (possible) power-law component poses a puzzle. It has been suggested that this component is due to accretion onto the NS magnetosphere (Campana et al. 1998). However, such accretion would be unrelated to the quiescent luminosity of NSs as predicted from deep crustal heating (which is dominated by outburst accretion), and it can only be ascribed to coincidence that in the cases where adequate sensitivity is obtained, the power-law component produces a comparable fraction of the thermal flux in different sources. This suggests that the power-law component and H atmosphere spectral component are perhaps more closely related than previously thought.

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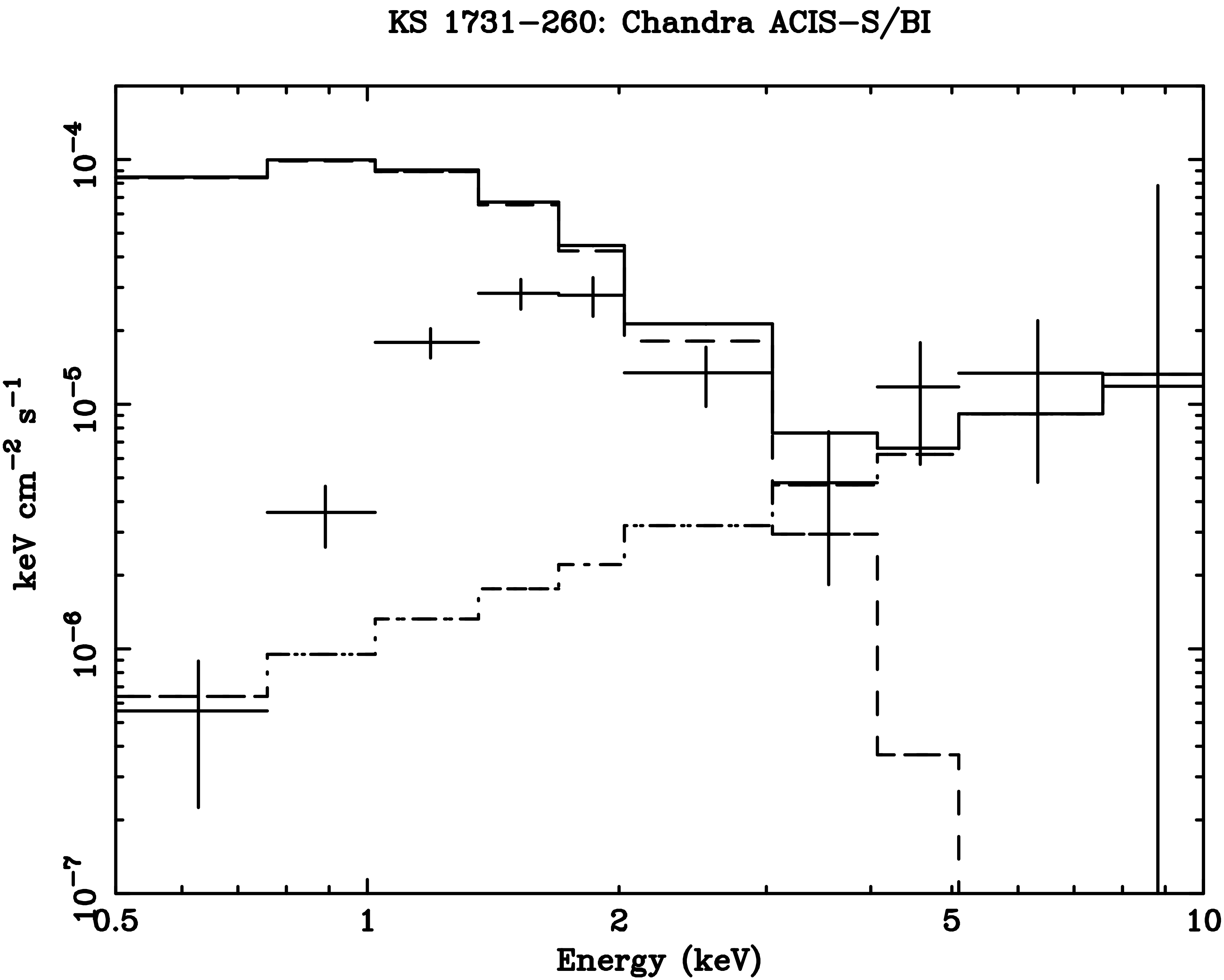
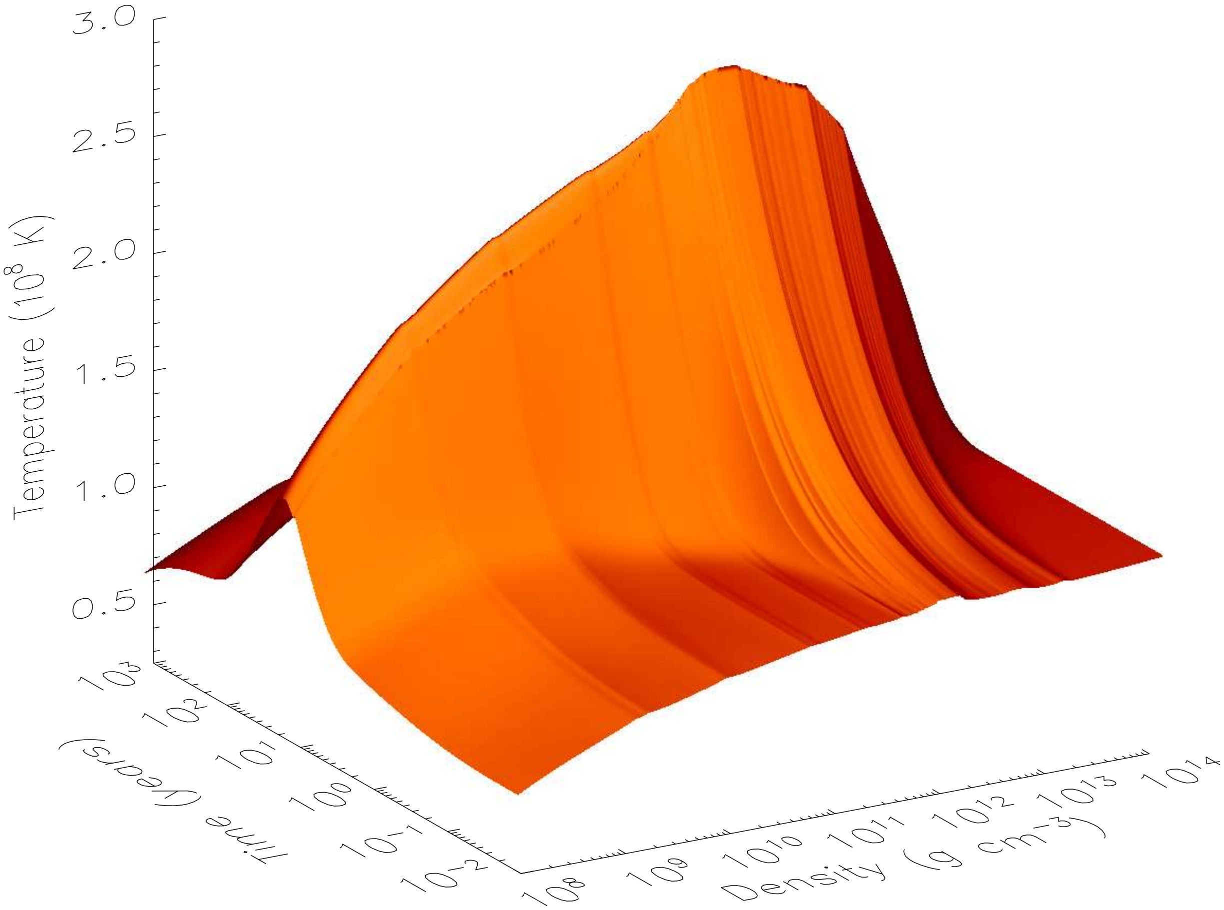
FIG. 1.— The νF_ν model spectrum of KS 1731-260, and the observed *Chandra*/ACIS-S BI data. The solid line is the best-fit unabsorbed spectrum (H atmosphere plus power-law, with R_∞=12.5 km and α=0.85 held fixed) . The dashed line is the H atmosphere component, the dashed-dotted line is the power-law component. The crosses are the observed *Chandra* data, with error bars in countrate. The two spectral components are equal near 3.5 keV, above which the power-law component dominates, and below which the H atmosphere component dominates.

FIG. 2.— Crustal temperature distribution as a function of time, for $\tau_{\rm outburst} = 13yr$, $3\times10^{-9}M_\odot$ yr^{-1}, recurrence time of 1500 yr, and deep crustal heating of $Q = 1.45$ MeV, using "low K" conductivity, and modified Urca neutrino emission from the core. The x axis is the density, y axis is time since the beginning of the outburst, and z axis is temperature.

FIG. 3.— Left panel **(a)**: time evolution of the quiescent luminosity assuming an outburst accretion rate of $3\times10^{-9}M_\odot$ yr^{-1}, recurrence time of 1500 yr, and deep crustal heating of $Q = 1.45$ MeV/accreted baryon. Solid and dotted lines are for low crustal conductivity (set by electron-impurity scattering), dashed and dash-dotted lines are for high crustal conductivity (electron-phonon scattering). Solid and dashed line correspond to simulations with standard neutrino cooling processes (modified Urca suppressed by nucleon superfluidity), dotted and dash-dotted lines – enhanced neutrino emission due to a core π condensate (with superfluid correction factors). Right panel **(b)**: same as **(a)**, except the nuclear energy release $Q_{\rm nuc}$ in the crust is adjusted to give $L_q \approx 2.7\times10^{33}$ erg s^{-1} just following the outburst. $Q_{\rm nuc}$ values are: solid line — 0.42 MeV, dotted line — 0.49 MeV, dashed line — 0.6 MeV, dash-dotted line — 3.1 MeV.



KS 1731−260: Chandra ACIS−S/BI
keV cm^{-2} s^{-1}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.5
1
2
5
10
Energy (keV)



3.0
2.5
2.0
1.5
1.0
0.5
Temperature (10^8 K)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Time (years)
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Density (g cm^{-3})

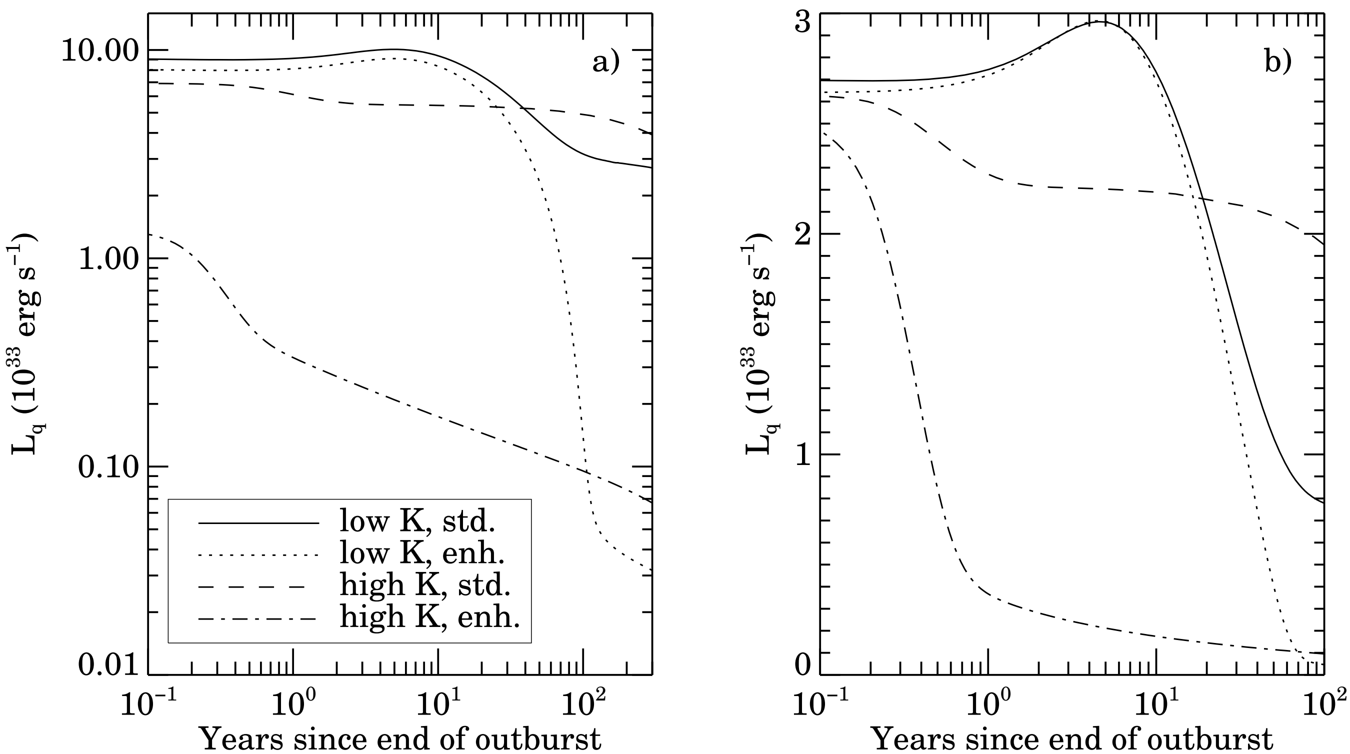

a)
b)
10.00
1.00
0.10
0.01
3
2
1
0
L_q (10^{33} erg s^{-1})
10^{-1}
10^{0}
10^{1}
10^{2}
Years since end of outburst
low K, std.
low K, enh.
high K, std.
high K, enh.

TABLE 1
DETECTED X-RAY SOURCES IN THE FIELD OF KS 1731–260

No.	R.A. (J2000)	Dec. (J2000)	Counts[a]
1 (KS 1731–260)	17h34m13.45s	–26d05m18.7s	180±13
2	17h34m12.68s	–26d05m48.3s	50±7

NOTE.—Positional uncertainty (from systematics of spacecraft pointing; http://cxc.harvard.edu/mta/ASPECT/celmon/) is $\sim 1''$.
[a] Total background subtracted counts in 19401 sec integration.

TABLE 2

Chandra SPECTRAL MODEL PARAMETERS OF KS 1731–260 (0.5-10 KEV)

Parameter	Value
H Atmosphere	
$N_{H,22}$	$1.0^{+0.3}_{-0.2}$
$kT^{\infty}_{\rm eff}$ (eV)	120 ± 30
R_{∞} (km)	6.5^{+6}_{-3}
Total Model Flux	1.8
χ^2_{ν}/dof (prob)	1.06/7 (0.39)
H Atm. + Power Law	
$N_{H,22}$	1.3 ± 0.3
$kT^{\infty}_{\rm eff}$ (eV)	90^{+40}_{-20}
R_{∞} (km)	23^{+30}_{-15}
α	$-0.1^{+1.4}_{-2.0}$
$F_{X,PL}$	0.2
Total Model Flux	3.1
χ^2_{ν}/dof (prob)	0.43/5 (0.83)
H Atm. + Power Law (R_{∞}, α fixed)	
$N_{H,22}$	1.06 ± 0.08
$kT^{\infty}_{\rm eff}$ (eV)	111 ± 3
R_{∞} (km)	(12.5)
α	(0.85)
$F_{X,PL}$	0.2
Total Model Flux	2.1
χ^2_{ν}/dof (prob)	0.47/7 (0.86)
Photon Power Law	
$N_{H,22}$	1.7 ± 0.4
α	5.2 ± 0.6
Total Model Flux	20.0
χ^2_{ν}/dof (prob)	0.94/7 (0.48)
Raymond-Smith	
$N_{H,22}$	$0.7^{+0.2}_{-0.1}$
Z ($Z_{\rm sol}$)	(1)
kT (keV)	1.4 ± 0.1
$\int n_e\, n_H\, dV$	$(6.2\pm1.5)\times10^{55}$
Total Model Flux	0.93
χ^2_{ν}/dof (prob)	2.32/7 (0.02)
Multicolor Disk	
$N_{H,22}$	1.1 ± 0.2
$T_{\rm in}$ (eV)	370 ± 50
$R_{\rm in}\sqrt{\cos(\theta)}$ (km)	$0.7^{+0.5}_{-0.3}$
Total Model Flux	2.0
χ^2_{ν}/dof (prob)	1.1/7 (0.37)
Blackbody	
$N_{H,22}$	0.90 ± 0.2
$kT^{\infty}_{\rm eff}$ (eV)	300 ± 40
R_{∞} (km)	$1.3^{+0.6}_{-0.4}$
Total Model Flux	1.3
χ^2_{ν}/dof (prob)	1.11/7 (0.35)

NOTE.—X-ray fluxes are un-absorbed, in units of 10^{-13} erg cm^{-2} s^{-1} (0.5-10 keV). Uncertainties are 1σ. Values in parenthesis are held fixed. Assumed source distance d=8 kpc.